Glaciological conditions in northern Switzerland during recent Ice Ages

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Abstract: Based primarily on reconstructions and various model calculations, quantitative estimates are compiled concerning ice conditions in northern Switzerland during the past Ice Age. The penetration of winter sea ice to low latitudes and the corresponding closure of the Atlantic Ocean as a humidity source caused extremely cold/dry conditions in central Europe during the time period of maximum cold and most extended area of surface ice. At this stage, the large lobes of the piedmont glaciers spreading out over much of the Swiss Plateau were predomi- nantly polythermal to cold, surrounded by continuous periglacial permafrost up to 150 m thick and characterised by low driving stresses (typically 30 to 50 kPa). Mass balance gradients, mass turnover and ice flow velocities on these piedmont glaciers were correspondingly low. Sub- surface temperatures and groundwater conditions were strongly influenced by the presence of extended surface and subsurface ice. Glacial erosion in the ice-marginal zones was probably limited due to strongly reduced basal sliding and melt-water flow. More humid conditions with higher flow velocities, more basal sliding and stronger erosion by abrasion and melt-water effects must have prevailed during ice advance across the Swiss Plateau, and rapid down- wasting or even collapse (calving instability in lakes) is likely to have taken place during the retreat phase back into the Alpine valleys. It appears plausible to assume that similar cycles were characteristic for past Ice Ages in general and could also be characteristic for future Ice Age conditions in northern Switzerland. Some key questions concerning effects of deep glacial erosion are formulated.

Arbeitsbericht NAB 10-18

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December 2010

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KEYWORDS

Ice ages, ice age climate, paleoglaciology, periglacial, polythermal glaciers, permafrost, glacial erosion and sedimentation

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Abstract

Based primarily on reconstructions and various model calculations, quantitative estimates are compiled concerning ice conditions in northern Switzerland during the past Ice Age. The penetration of winter sea ice to low latitudes and the corresponding closure of the Atlantic Ocean as a humidity source caused extremely cold/dry conditions in central Europe during the time period of maximum cold and most extended area of surface ice. At this stage, the large lobes of the piedmont glaciers spreading out over much of the Swiss Plateau were predominantly polythermal to cold, surrounded by continuous periglacial permafrost up to 150 m thick and characterised by low driving stresses (typically 30 to 50 kPa). Mass balance gradients, mass turnover and ice flow velocities on these piedmont glaciers were correspondingly low. Subsurface temperatures and groundwater conditions were strongly influenced by the presence of extended surface and subsurface ice. Glacial erosion in the ice-marginal zones was probably limited due to strongly reduced basal sliding and melt-water flow. More humid conditions with higher flow velocities, more basal sliding and stronger erosion by abrasion and melt-water effects must have prevailed during ice advance across the Swiss Plateau, and rapid down-wasting or even collapse (calving instability in lakes) is likely to have taken place during the retreat phase back into the Alpine valleys. It appears plausible to assume that similar cycles were characteristic for past Ice Ages in general and could also be characteristic for future Ice Age conditions in northern Switzerland. Some key questions concerning effects of deep glacial erosion are formulated.

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1 Introduction

The National Cooperative for the Disposal of Radioactive Waste (Nagra) is in charge of implementing deep geological repositories in Switzerland. This also includes proposing sites for such repositories and performing analyses of their long-term safety. As part of these safety analyses the evolution of surface and subsurface conditions has to be evaluated for a time horizon of one million years for the disposal of high-level waste. One of the relevant aspects concerns the effects from large piedmont glaciers that extended from the Alps far into the Alpine foreland, covered the midland areas of northern Switzerland (Swiss Plateau) with hundreds of meters thick ice several times during the Quaternary and were connected to thick sub- and periglacial permafrost. As the climate in northern Switzerland in the time period of concern (1 Ma) is expected to continue to oscillate between glacial and interglacial periods, quantitative information about Ice Age ice conditions and their effects is of great importance for the siting and long-term safety of radioactive waste repositories. Of significance in this respect is that all of the proposed geological siting regions are located within the surface-ice extent during the Most Extensive Glaciation (MEG), some of them even within that at the Last Glacial Maximum (LGM).

The present study is an attempt to provide an overview of the available information concerning "Ice Age glaciology" in northern Switzerland for the NAGRA/UZH Workshop on Glacial Erosion Modelling, 29 April – 1 May 2010, Ägerisee, Switzerland. It represents a focussed/updated translation of an earlier report in German (Haeberli 2004), briefly dealing with aspects of Ice Age climate (air temperature, precipitation, atmospheric circulation), Ice Age paleoglaciology (flow, mass turnover and temperature of glaciers; temperature and thickness of permafrost) and past glacial and periglacial geomorphology (glacial and periglacial erosion, sedimentation). Emphasis is on quantitative studies about the time of maximum cold/maximum ice extent around 24'000 years ago. Corresponding scientific work on quantitative Ice Age glaciology only started during the past decades. This paleoglaciology of northern Switzerland is still in a somewhat initial stage but nevertheless already provides important insights.

2 Ice Age climate in central Europe

Quantitative reconstructions from various evidences in nature such as pollen analysis or permafrost indicators, etc. (cf. Frenzel et al. 1992) together with climate modelling have created a rather plausible view of the specific climatic conditions existing during the coldest part of the Last Ice Age (Würm, Weichsel, Wisconsin) in central Europe with maximum ice extent in northern Switzerland (cf. Jäckli 1970; Kelly et al. 2004; Schlüchter/swisstopo 2010) around 24'000 years ago (cf. also Denton & Hughes 1981; Boulton & Payne 1994).

The general distribution of glaciers and permafrost depend on the degree of continentality in climatic conditions (cf. the scheme in Figure 1): temperate, active glaciers with high mass balance gradients and comparably large mass turnover, high driving stresses and tongues often reaching permafrost-free forested areas tend to predominate in regions with a humid-maritime climate, while regions with a dry-continental climate are characterised by widespread periglacial permafrost and comparably less active polythermal to cold glaciers with low mass balance gradients, reduced mass turnover/driving stresses and lower margins often frozen to their bed. Mean annual air temperature (MAAT) at glacier equilibrium lines (T_E) or at glacier mid-range altitudes (Braithwaite & Raper 2009) thereby functions as a key indicator of climatic and glaciological conditions. MAAT-values derived from paleopermafrost indicators (especially ice wedge casts in Loess regions) can be used to estimate T_E values and combined with reconstructed mean summer air temperatures (MSAT) from pollen analysis to calculate seasonal paleotemperatures. Pollen spectra (for the vegetation period), T_E and the amplitude of seasonal temperature fluctuations provide information on paleoprecipitation (cf., for instance, compilations by Frenzel et al. 1992 for the northern hemisphere (see Appendix); Washburn 1979; Vandenberghe & Pissart 1993; Ballantyne & Harris 1994; French 1996/2007 for Europe (Figure 2); Haeberli 1983, 1991b for the Alps).

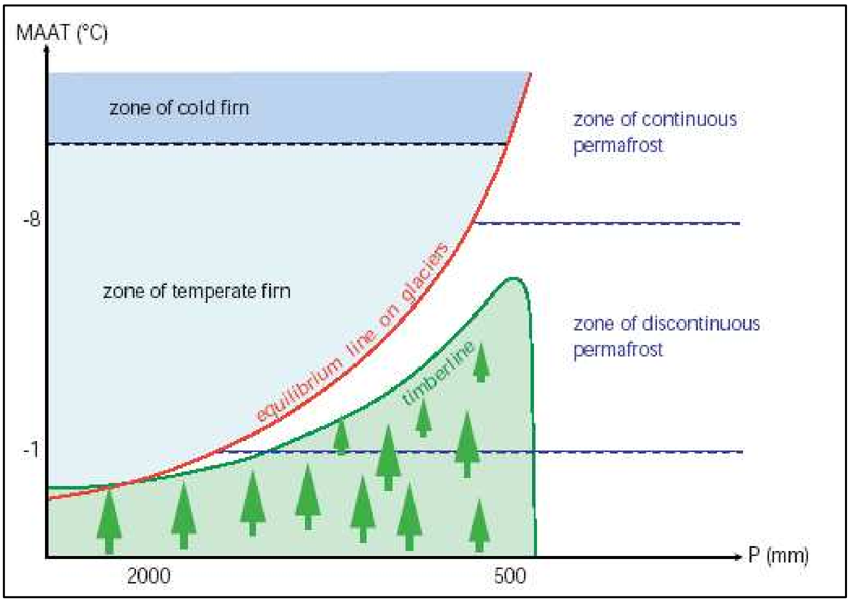


Fig. 1: Scheme of glacier, permafrost and forest distribution as related to mean annual air temperature and annual precipitation (from Haeberli & Burn 2002).

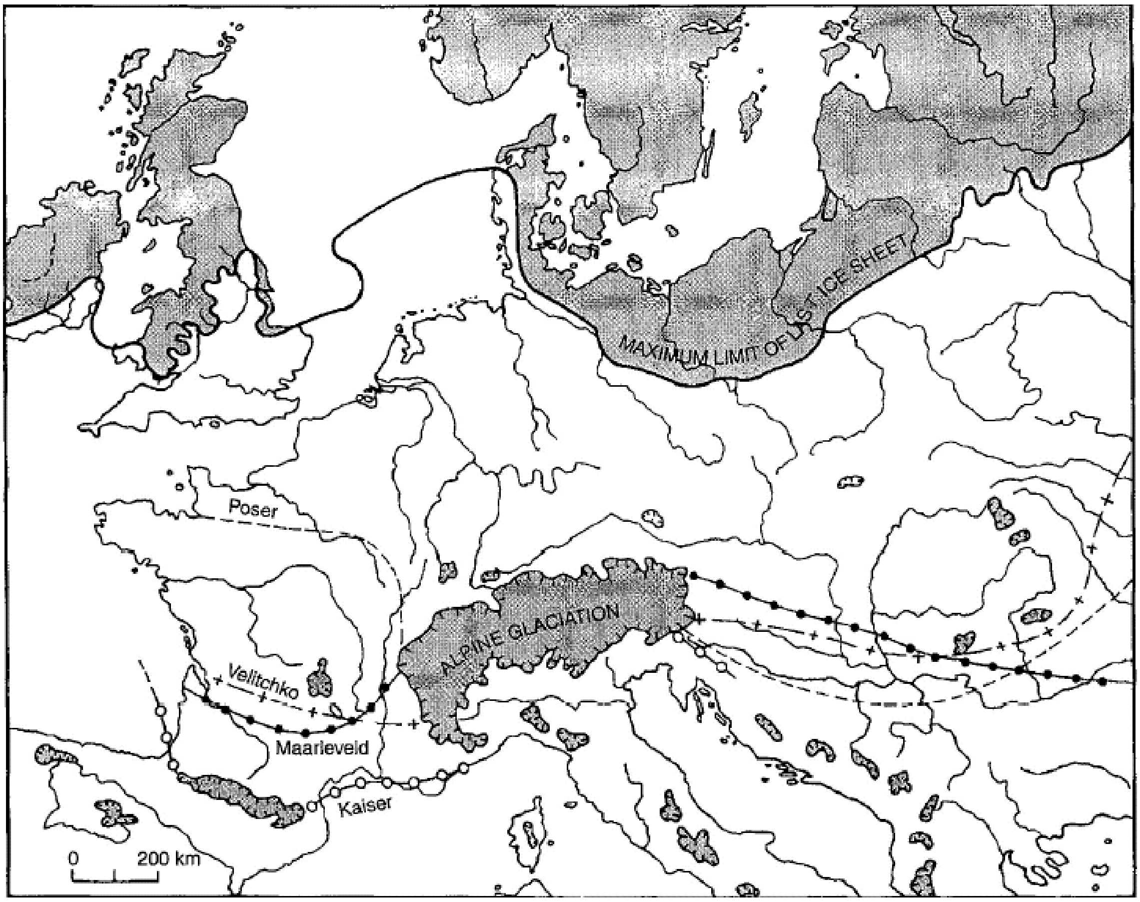


Fig. 2: Southern limit of continuous permafrost in central Europe during LGM after various authors (from French 1996).

During the coldest period of the Last Ice Age, continuous permafrost with a bush tundra (no forest) existed north of the Alps, surrounding glaciers with T_E far below -10 °C, and a cold-arid climate existed in central Europe and northern Switzerland. MAAT-values could have been lower than today by up to 15 °C, winter temperatures by 25 °C but summer temperatures by 5 °C only (Figure 3). In accordance with evidence from pollen spectra, the enhanced amplitude of seasonal temperature variations indicates strong reduction (to about 20 % of recent values) in annual precipitation in the time of coldest temperatures.

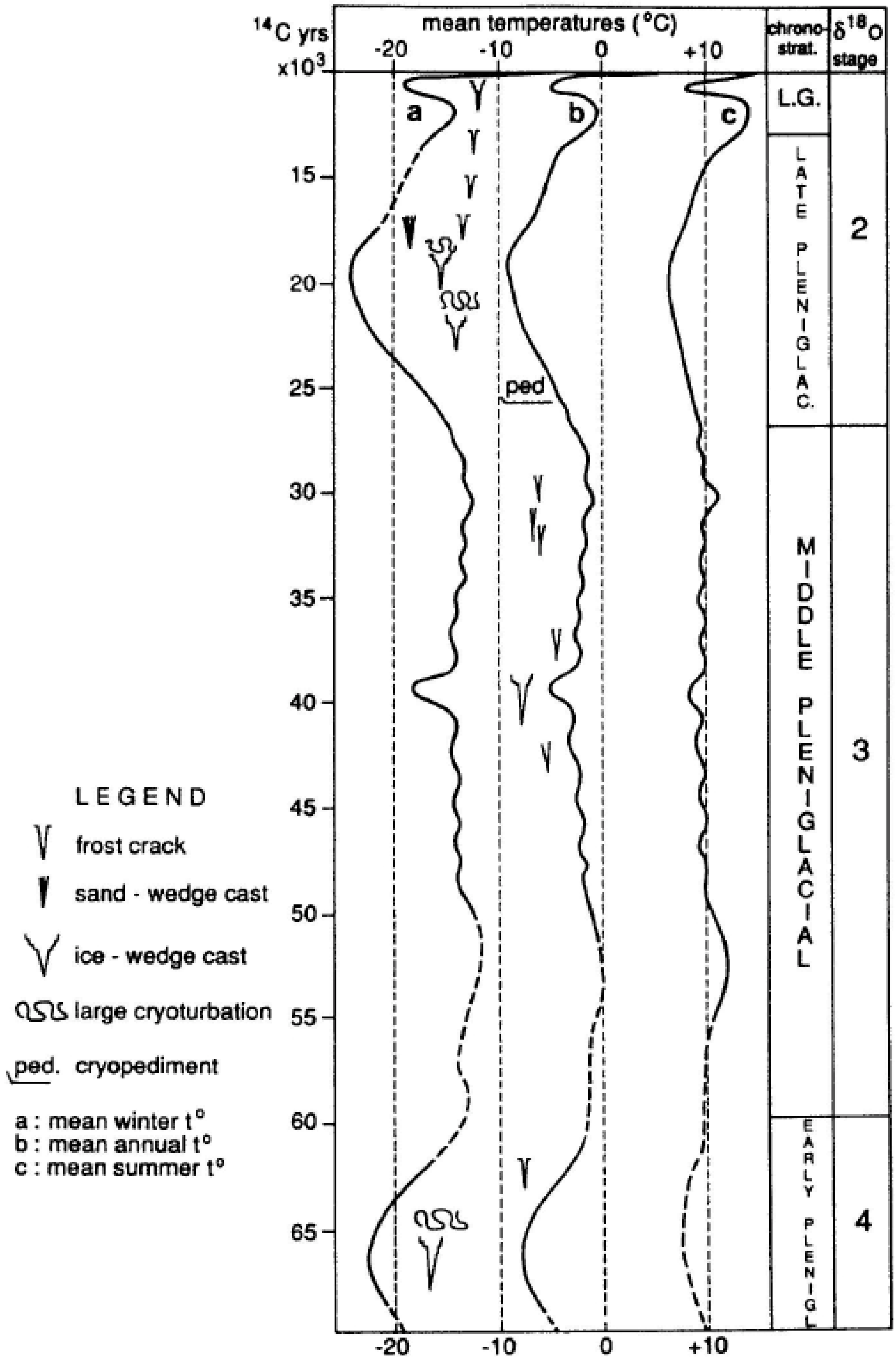
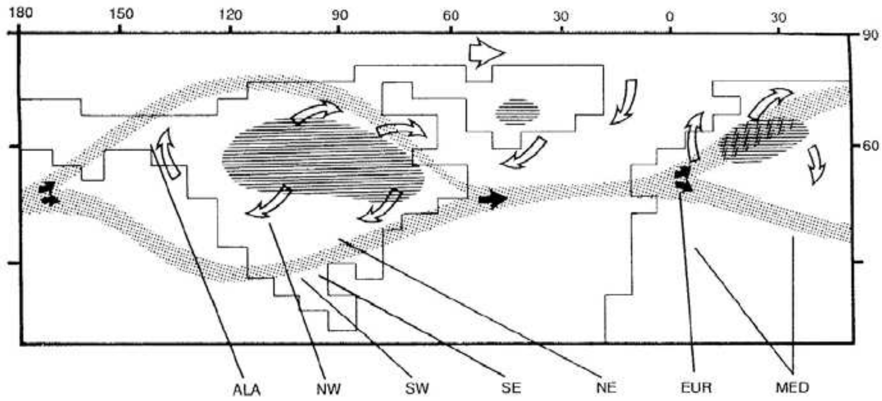


Fig. 3: Mean annual, summer and winter temperatures during the Weichselian Pleniglacial and Lateglacial in the Netherlands and Belgium (from Vandenberghe & Pissart 1993).

Already the first GCM Ice Age experiments (Manabe & Broccoli 1984) clearly showed the important influence of the Laurentide Ice Sheet for the Atlantic Ocean and the climate in central Europe: the strong and stable anticyclone forming over the cold high-elevation surface of this enormous ice sheet deviated a branch of the Pacific jet stream via the Polar Ocean (Figure 4) and – as an extremely cold and dry air mass – towards the Atlantic Ocean, where winter sea ice was driven as far south as the Pyrenees (cf. Appendix). This at least temporarily (wintertime) closed down the Atlantic Ocean as a primary humidity source for central Europe and caused a shift of the polar front towards the Mediterranean Sea (Florineth & Schlüchter 1998). As a consequence, the Alps became a most efficient meteorological divide for the primary humidity source in the South. Large-scale subsidence from the Scandinavian ice sheet in the North, katabatic winds from the large Alpine glaciers and cold air pockets dammed by the Jura Mountains may have further strengthened cooling in northern Switzerland far below average global temperature change (a few °C).



	ALA	NW	SW	SE	NE	EUR	MED
ΔT (K) JAN	5 / 10	-5 / -10	0 / -5	0 / -5	-5 / -10	-20 / -25	-10 / -15
ΔP (%) JAN	-25 / -30	-0	30 / 35	-0	-0	-10 / -15	-25 / -30
Δ(P-E) (%) ANN	-45 / -50	-15 / -20	80 / 85	-25 / -30	-10 / -15	-70 / -75	0 / -5
ΔT (K) JUL	0 / -5	-5 / -10	0 / -5	0 / -5	-5 / -10	0 / -5	0 / -5
ΔP (%) JUL	-40 / -45	-25 / -30	-25 / -30	-25 / -30	-10 / -15	-5 / -10	5 / 10

Fig. 4: Generalised pattern of the northern hemisphere circulation for January 18,000 BP. Note the pattern of split jet stream flow around both the Eurasian and Laurentide ice sheets (from Dawson 1992).

Advanced AOGCM-modelling (for instance, Budd et al. 1998; Gildor & Tziperman 2001) demonstrate the various feedbacks and interactions within the climate system, especially the teleconnection between ice sheet build up, the thermo-haline circulation and the fast spreading of sea ice in the Atlantic Ocean for progressive cooling/drying towards the terminal phases of Ice Ages (Figure 5).

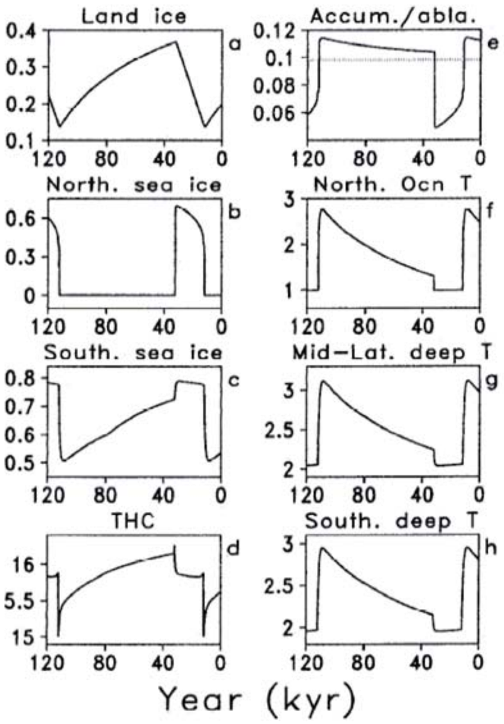


Fig. 5: Time series of model results during one complete glacial-interglacial cycle (from Gildor & Tziperman 2001).

(a) Northern land ice extent as a fraction of the polar land box area; (b) northern sea-ice extent as a fraction of polar ocean box area; (c) southern sea-ice extent as a fraction of polar ocean box area; (d) THC through the northern polar boxes (10^6 m^3 s-1); (e) source term (solid line) and sink term (dashed line), for northern land glacier (10^6 m^3 s-1); (f) temperature in the northern upper polar oceanic box (°C); (g) temperature in the mid-latitude deep oceanic box (°C); (h) temperature in the southern deeper polar oceanic box (°C).

Such results make it plausible that cold-arid conditions regularly develop in central Europe – in future Ice Ages as well. Simulations of future global climate evolution in view of irregularities in the Earth's orbital parameters (Laskar et al. 1993) point to extraordinarily small amplitudes in the fluctuations of northern-hemisphere solar irradiation for the coming 130'000 years and a possible onset of the next Ice Age in about 70'000 years only (Loutre & Berger 2000). The long-term legacy of fossil fuel burning could, however, delay this much more (Tyrrell et al. 2007).

3 Ice Age paleoglaciology of northern Switzerland

Surface and subsurface ice affected the entire region during the coldest/driest stages towards the end of the past Ice Age: the large piedmont glaciers covering most of the Swiss Plateau were surrounded by continuous periglacial permafrost. Both, permafrost and glaciers, have been treated quantitatively but the interaction between the two as well as corresponding effects on groundwater flow and deep subsurface temperatures remain a strongly under-researched field of science needing much more work (cf. Haeberli 2005).

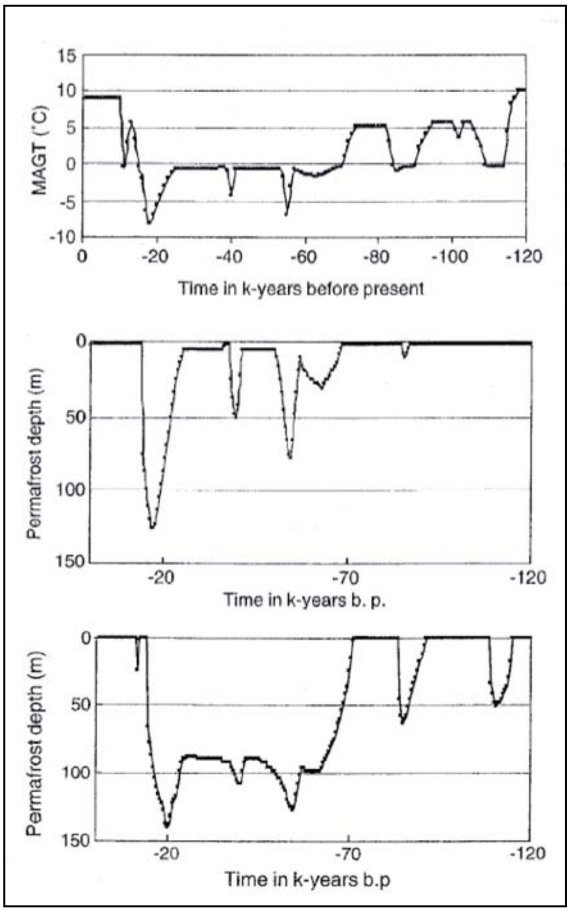


Fig. 6: Permafrost-thicknesses in northern and central Europe during the last Ice Age based on reconstructed mean annual ground surface temperatures (MAGT, upper graph) for sites with snow and vegetation cover (middle graph, topographic depressions) and on mean annual air temperatures (MAAT) for snow- and vegetation-free sites (lower graph, wind-exposed ridges) (from Deslisle et al. 2003).

With mean annual ground surface temperatures (MAGST) getting as deep as -5 °C or even colder, periglacial permafrost thickness in northern and central Europe probably reached maximum values of up to 150 meters towards the end of the past Ice Age (Deslisle et al. 2003). Snow cover influences the results of the model simulation mainly with respect to the length of the time period rather than maximum penetration depths of perennially frozen ground (Figure 6). In view of the reduced winter precipitation from the ice-covered Atlantic Ocean, the strong shielding effect by the Alps against humidity advection from the Mediterranean Sea and the likely formation of cold air pockets in the Plateau, it may be reasonable to assume MAGST-values in northern Switzerland as cold as in central and northern Europe. Discontinuous permafrost still persisted in lowlands of northern Europe during the Younger Dryas time (Isarin et al. 1998) while it had retreated to high altitudes in the Alps (Frauenfelder et al. 2001). Remains of subsurface ice are rather unlikely to have still existed in the Swiss Plateau at the onset of the Holocene (Figure 7; Haeberli et al. 1984). Presently existing knowledge about subglacial permafrost below ice-age glaciers is much more uncertain than concerning periglacial permafrost. Interglacial ice-age permafrost indeed depends on the characteristics and flow dynamics of the large piedmont glaciers and tends to be warmer/thinner than permafrost outside glaciated areas.

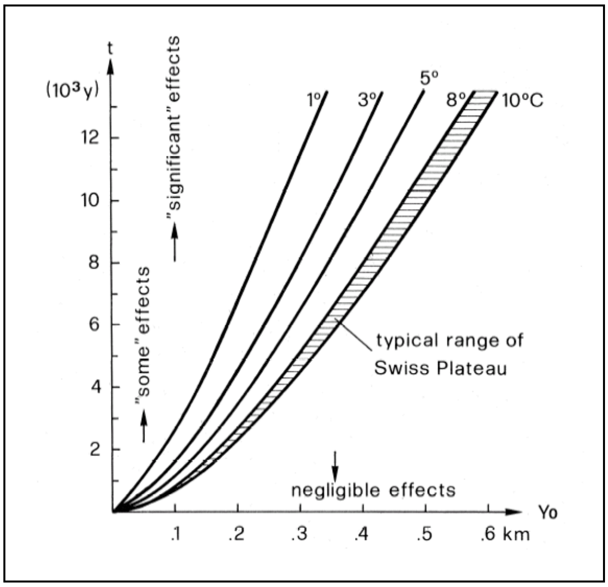


Fig. 7: Time (t) necessary for complete thawing of ice-saturated permafrost (about 35 % pore volume) as a function of initial (maximum) thickness (y_0) (from Haeberli et al. 1984).

The surface geometry for the maximum extent of the last Ice Age as compiled by Jäckli (1970) has recently been revised and updated by Schlüchter/swisstopo (2010). This latest version especially also includes the reconstructed ice cap over the southern Jura Mountains (Aubert 1965) and the dome-like culminations in the Engadin and in the central Alps with outward flow towards all directions. The detailed mapping and reconstructions of the Rhine glacier (Keller & Krayss 1991; Keller 1994) constituted a unique basis for a GIS-based analysis of this large Ice Age piedmont glacier (Figures 8, 9; Benz 2003).

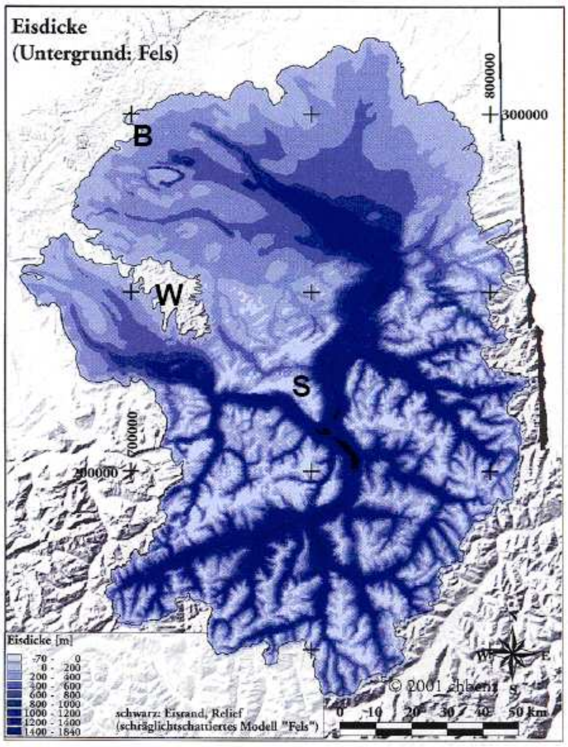


Fig. 8: GIS-based reconstruction of LGM ice thickness to bedrock for the Rhine Glacier (B = Benken, S = Sargans, W = Winterthur) (from Benz 2003).

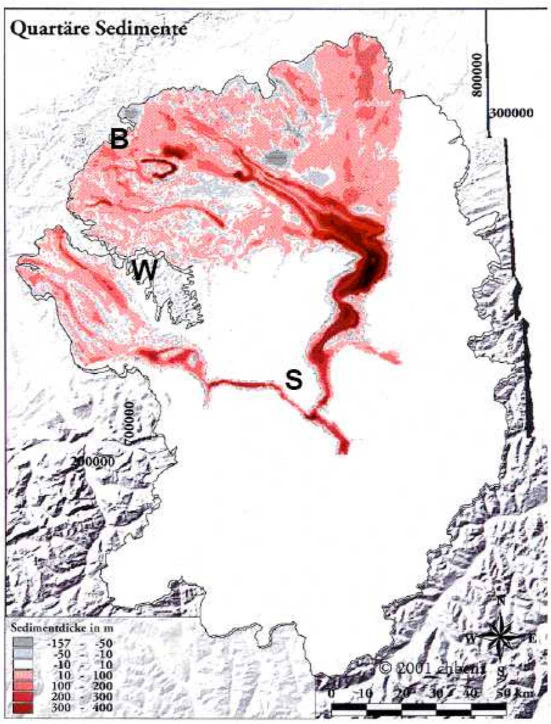


Fig. 9: GIS-based reconstruction of quaternary sediment thickness in the area of the LGM Rhine Glacier (B = Benken, S = Sargans, W = Winterthur) (from Benz 2003).

A first attempt to calculate driving stresses, flow velocities and mass balance gradients for all major Ice Age glaciers in Switzerland during their maximum extent was undertaken by Haeberli & Penz (1985; cf. also Körner 1983; Haeberli & Schlüchter 1987). Basal shear stresses (Figures 10, 11) along the central flowlines of the large piedmont lobes in the Swiss Plateau were very low (30 to 50 kPa). This is a robust result, which cannot be explained by rapid subglacial deformation of water-saturated sediments (cf. Boulton & Jones 1979; Haeberli 1981).

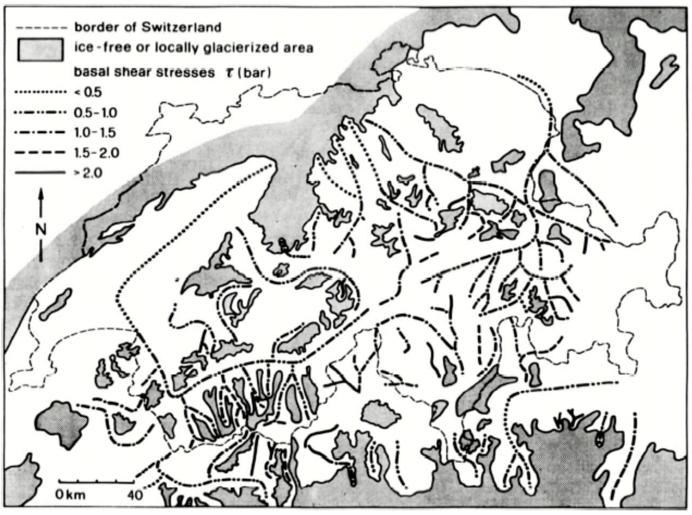


Fig. 10: Basal shear stresses of 18 ka BP Ice Age glaciers in and around the Swiss Alps. Values are averaged over distances greater than 10 times the local ice thickness (from Haeberli & Penz 1985).

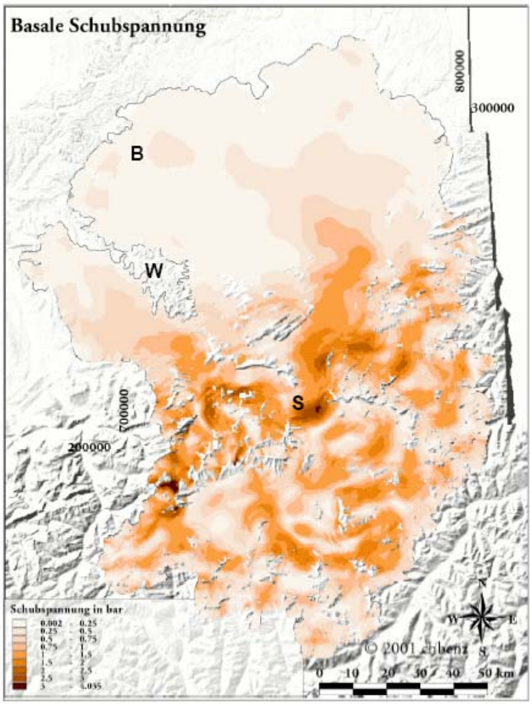


Fig. 11: GIS-based reconstruction of basal shear stresses in the area of the LGM Rhine Glacier (B = Benken, S = Sargans, W = Winterthur) (from Benz 2003).

Ice flow velocities (Figures 12, 13) calculated from the obtained driving stresses and calibrated against modern measurements, using the ice flow law and a rough assumption about possible basal sliding (velocity ratio = 0.5) are more uncertain (probably within one order of magnitude) but nevertheless striking: the movement of the enormous piedmont lobes must have been very slow (typically meters to tens of meters per year), effecting a low mass turnover and, hence, reflecting very low mass balance gradients (in the ablation zone 0.1 m per year per 100 m altitude or even lower).

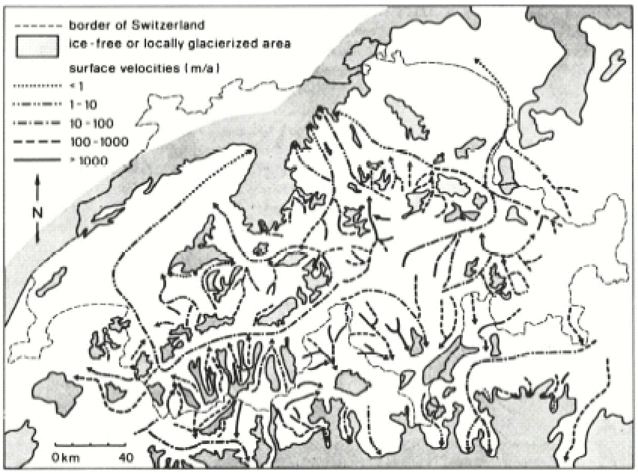


Fig. 12: Surface velocities of 18 ka BP Ice Age glaciers in and around the Swiss Alps. Values are averaged over distances of 10 km (from Haeberli & Penz 1985).

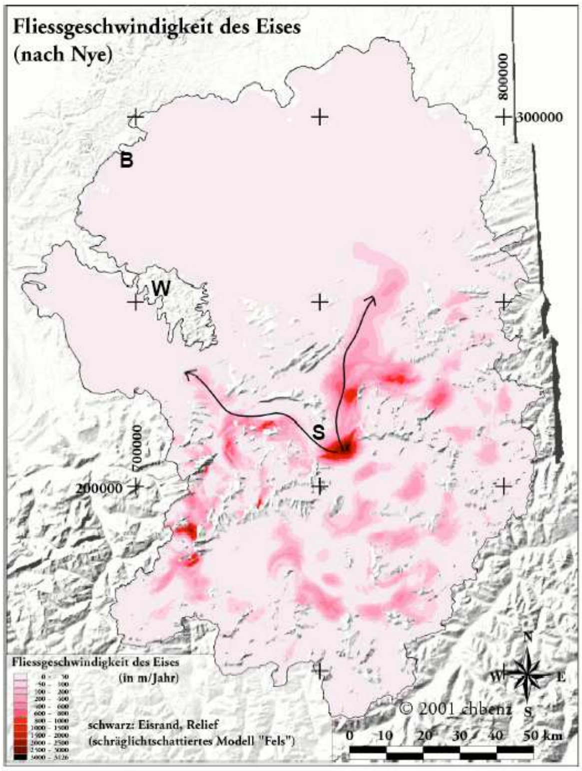


Fig. 13: GIS-based reconstruction of ice flow velocities in the area of the LGM Rhine Glacier (B = Benken, S = Sargans, W = Winterthur) (from Benz 2003).

Such conditions are indeed characteristic for dry-continental climate conditions. Glaciers on the southern slope of the main Alpine chain were clearly more active – a difference which is again a robust and plausible result.

Much higher stresses and flow rates are calculated for the former firn areas. This may indicate that the reconstructions given by Jäckli (1970) and Schlüchter/swisstopo (2010) could indeed be time-transgressive in that the geometry of the firn areas as reconstructed from upper limits of polish/striation-features could represent an earlier, more humid advance phase of the glaciers than the cold-dry terminal phase with ablation areas reconstructed from the outermost lateral and terminal moraines. In fact, the flow velocities calculated for the maximum extent of the piedmont lobes would not have enabled the ice to advance to its final position within the given limits of time. It is therefore plausible to assume that the ice build-up in the Swiss Plateau took place under the influence of a more humid climate with higher mass balance gradients, higher ice flow rates and higher englacial temperatures and that dry conditions with polythermal to cold and slow ice progressively developed towards the final time period of maximum glacier extent (cf. Haeberli 1991b; Ammann et al. 1994; Wohlfahrt et al. 1994). Blatter & Haeberli (1984) presented the first temperature model (Figure 14) of an Ice Age glacier in the Swiss Plateau. Despite its strong limitations (2D and steady state), this model illustrated the important influence of vertical and horizontal ice advection. Under the influence of geothermal heat, heat from ice deformation and basal friction, temperate basal ice may nevertheless have existed underneath the interior parts of the piedmont lobes even during the coldest periods, but the ice margins were most probably frozen to their bed, enabling at places ductile glaciotectonic deformation of ice-rich sediments in sub- and proglacial permafrost (Schindler et al. 1978).

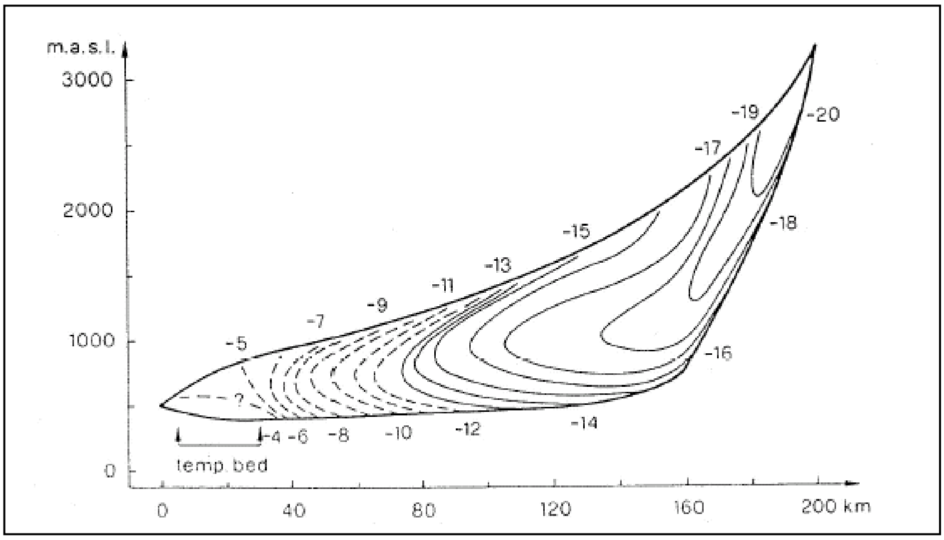


Fig. 14: LGM Rhine glacier, 18 ka BP: calculated 2D temperature distribution. Broken lines indicate regions of numerical instability in the calculation (from Blatter & Haeberli 1984).

Speck (1994) provided first numerical experiments on the interactions between glaciers, permafrost, groundwater and geothermal anomalies for Ice Age conditions in the Swiss Plateau (Figure 15), indicating that steep hydraulic gradients in the ice-marginal zone could cause strong vertical groundwater flow and deep-reaching geothermal anomalies.

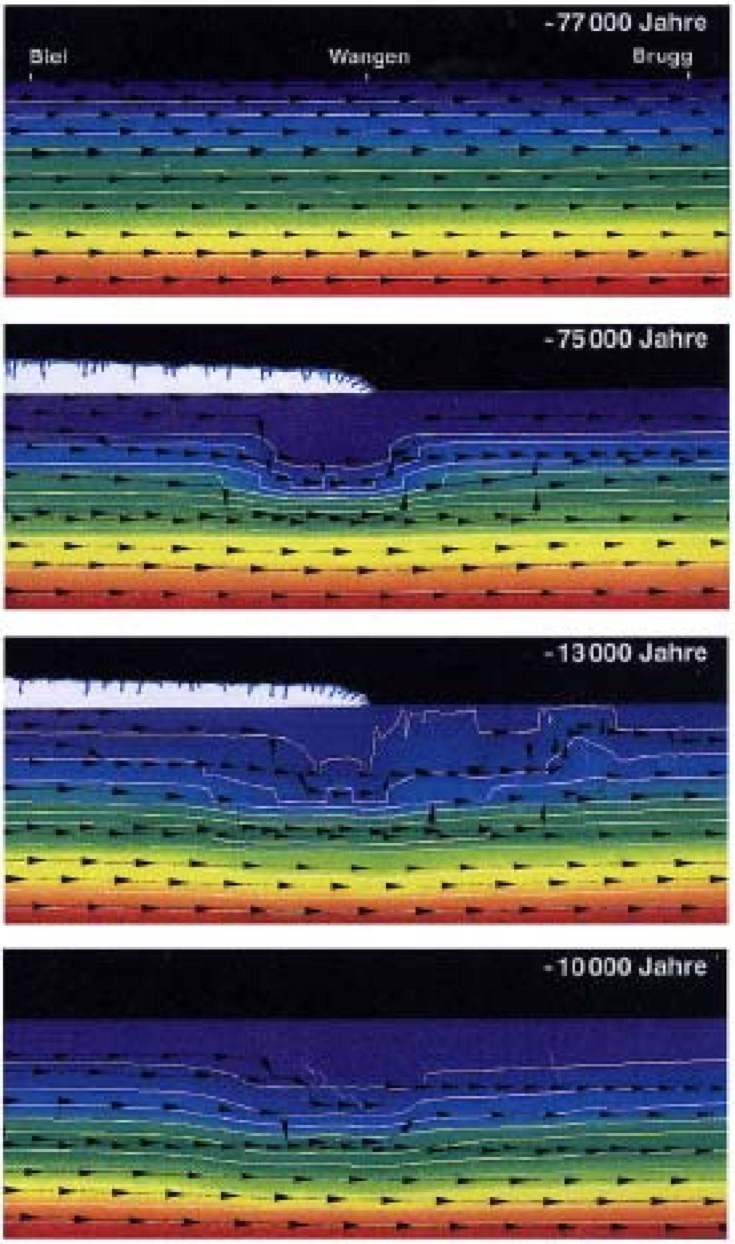


Fig. 15: Coupled glacier-groundwater model simulation for the LGM Rhone Glacier (from Speck 1994).

The existence of impermeable permafrost underneath the ice margins and in proglacial areas further complicates the relation (cf. also Boulton et al. 1995, 1996 concerning similar studies for northern Europe). The strong simplifications of the model (no transient effects, simplified lithology, continued groundwater flow from the upper catchment area) limit the possibilities of quantitative interpretation from this general study – the corresponding processes deserve intensified research (cf. Piotrowski 2006). Model calculations of complex thermo-mechanical and hydraulic effects from a cold ice margin advancing over periglacial permafrost have been carried out by Boulton & Hartikainen (2003), showing the degradation of the overridden permafrost and the building up of large hydraulic gradients as a consequence of reduced cross sectional area for groundwater flow (cf. also the qualitative considerations by Haeberli 1981).

4 Deep subsurface incisions in northern Switzerland – erosion and sedimentation under conditions of maximum cold/ice extent

Large amounts of sediments deposited in northern Switzerland cover and hide a considerable number of deep bedrock incisions at depth (Figures 9, 16; Schlüchter 1979; Benz 2003; Jordan 2007).

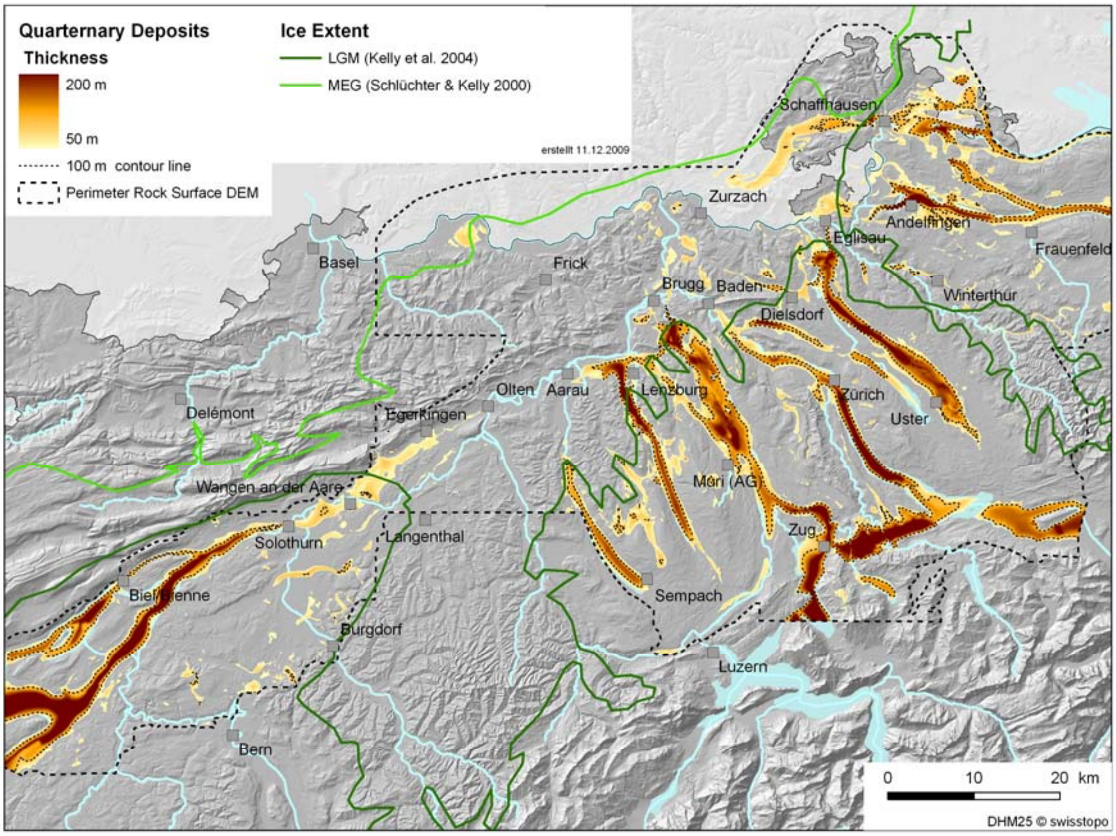


Fig. 16: Deep subsurface incisions in northern Switzerland (from Jordan 2007).

These incisions are up to 80 km long and commonly a few hundred meters to a few kilometres wide. Their mean depth is about 200 m with maximum values of up to 500 m and their valley floors often contain several highs and lows, in places even bedrock eminences. In most cases, the orientation of the incisions is parallel to the assumed former ice flow. All incisions are situated within the extent mapped by Schlüchter & Kelly (2000) for the Most Extensive Glaciation (MEG) but only some of them end within the ice extent during the LGM defined by Kelly et al. (2004) and Schlüchter & Kelly (2000). These arguments support the assumption of a glacial formational process but also seem to confirm that the incisions are older than the LGM. In a discussion of processes related to the formation of such deep incisions, a variety of aspects have to be considered, especially

- Sediment fluxes and the distribution of sediment/rock beds

- Glacial and periglacial contributions to catchment-area denudation
- Subglacial erosion in different bed materials and by different processes
- Specific influences of polythermal ice temperatures and sub-/periglacial permafrost

Such aspects concern the primary questions to be assessed in the planned 2010 NAGRA/UZH Workshop on Glacial Erosion Modelling and can only be dealt with here in a short introductory fashion. Simple answers may not exist (cf. overviews by Sugden & John 1976; Drewry 1986; Sommerfield 1991; Benn & Evans 1998; Bennett & Glasser 2009) and extreme disequilibria are likely to develop during transitions from cold to warm conditions (Hinderer 2001; Ballantyne 2002, 2003).

As glaciers constitute a transfer of rock particles, the ratio between input and output of debris primarily decides on sediment fluxes within glacier systems and on the characteristics of glacier beds. A corresponding index for predicting rock and sediment beds of mountain glaciers was introduced by Haeberli (1986, 1996), later applied to glacier inventory data (Maisch et al. 1999) and implemented in a GIS (Zemp et al. 2005). In its simplest ("light") version (optimally suitable for field observation and interpretation) it relates rock-wall height (for input) with the transport capacity of the melt water stream (for output) given by the product of mean precipitation and glacier area (runoff) times the average inclination of the melt water stream leaving the glacier margin. The approach is calibrated by observed conditions in glacier forefields exposed by ice retreat since the Little Ice Age and appears to be quite robust and realistic. It predicts mixed rock/sediment beds for LGM ice conditions in northern Switzerland as both, debris input from the distant, relatively small rock faces to the enormous and high-reaching ice masses, as well as sediment evacuation on flat terrain and by dry-climate melt water streams must have been limited. Such considerations neglect the uptake of sediments at the glacier bed – a process, which could increase in importance with growing glacier size; they nevertheless indicate that the entire glacial/periglacial system rather than an isolated subglacial process should be taken into account and that the evacuation of sediments beyond the glacier margin, i.e. the activity of sub- and proglacial melt water, plays a key role. With the slope of the proglacial terrain becoming zero or even inverse, lake formation builds up efficient sediment traps – a rather common feature of Ice Age glaciers in northern Switzerland.

Estimated average rates of overall catchment-area denudation (effective erosion, sediment yield) on the basis of various methodologies and approaches show variability within several orders of magnitude. Within this variability range, denudation rates increase with catchment area-size and humid-maritime climatic conditions favouring temperate/sliding glaciers with large mass turnover, high amounts of meltwater and rapid flow (Hallet et al. 1996). The presence of periglacial rock walls with intense frost weathering leads to larger sediment yields (Drewry 1986). It is therefore useful to discriminate between periglacial "cirque-wall recession rates" and "spatially averaged denudation rates" (Delmas et al. 2009). Besides the separate determination of these two components, interactions and feedbacks could be essential: with increased debris input from cirque-walls to basal ice layers, abrasion due to friction from rock components embedded in ice ("Hallet friction"; Hallet 1981) may increase to an optimum with continuous sliding where further addition of debris and increased rock-to-rock contacts in the basal ice layer ("sandpaper friction"; Schweizer & Iken 1992) starts reducing basal sliding to stop-and-go motion and reduced abrasion if not sedimentation (Haeberli 1991a). Erosion rates tend to peak during the transition to ice-free conditions (Figure 17) with cliff recession predominating because of de-buttressing effects (cf. Hinderer 2001; Ballantyne 2002, 2003; Delmas et al. 2009). Extreme overall values (10 – 100 mm per year) are reported from large glacierised catchment areas in tectonically active humid-maritime mountain ranges of southern Alaska (Hallet et al. 1996). Cold-dry climatic conditions with slowly flowing, flat polythermal to cold piedmont glaciers with reduced mass turnover and limited melt-water availability would favour low overall erosion rates to even sediment deposition in northern Switzerland during LGM.

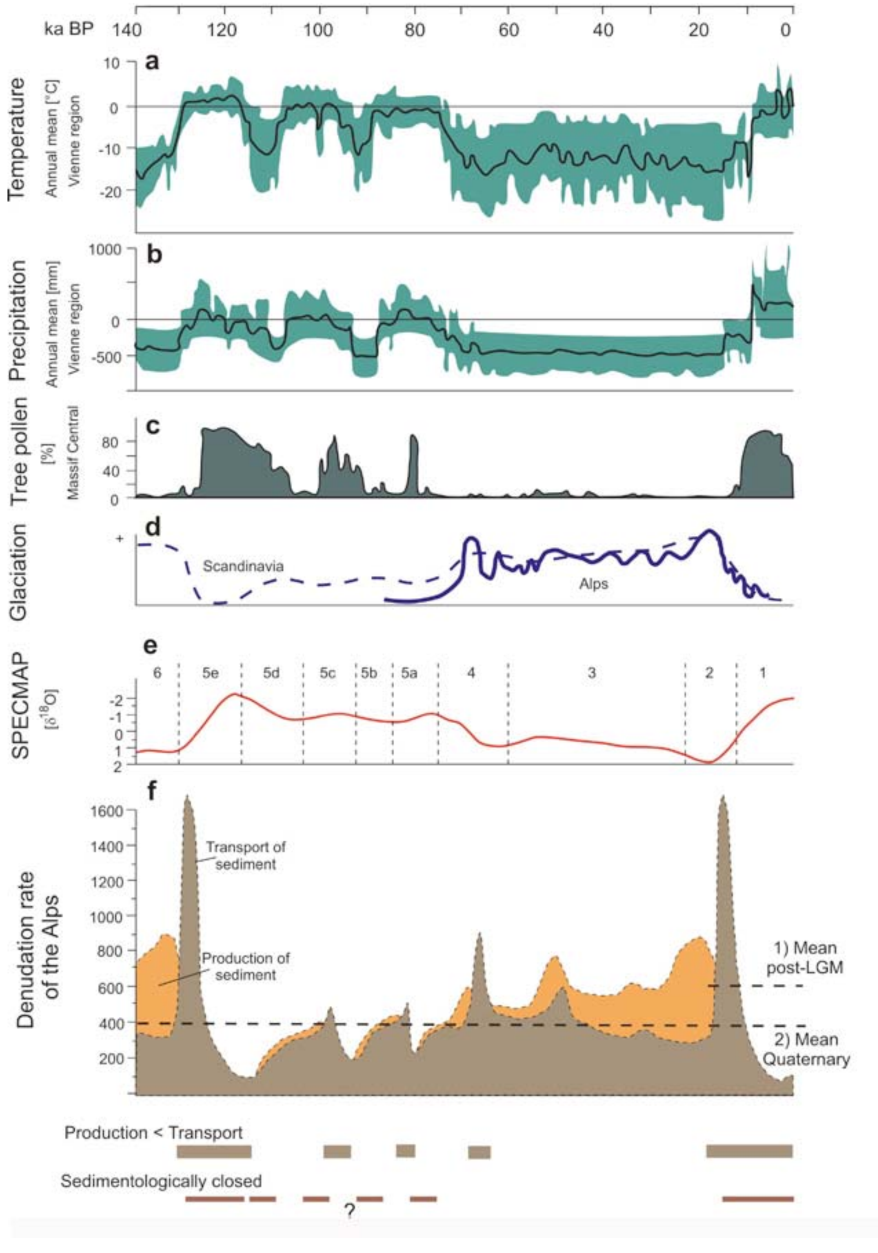


Fig. 17: Variations of denudation rates in the Alps during the past 140 ka (from Hinderer 2001).

Rates of glacial erosion depend on material characteristics of the subglacial bed. Taku Glacier (Juneau Ice Field) in its advance stage of the tidewater glacier cycle presently entrenches into soft basal sediments at rates, which can exceed 3 m per year (Motyka et al. 2006; Truffer et al. 2009). Erosion rates in gravel or ground moraine with larger rock components may be slower but complete emptying by glacial erosion of deep valleys previously filled with several hundred meters of such sediments obviously happened during the last Ice Age in some Alpine valleys now refilled with late- and postglacial sediments (Müller 1994, cf. also Lister 1988). This indicates that the glacial erosion and periglacial removal of thick sediment infill within deep incisions of northern Switzerland could be easily possible and may even take a relatively short time only. Bedrock erosion is much slower and usually attributed to abrasion, plucking and basal melt water erosion. Glacial striation and polish by coarser and finer material embedded within basal glacier layers is a spatially extended process, strikingly visible over large areas of exposed bedrock and perhaps the quantitatively predominant process of spatially averaged glacial catchment-area denudation. Concerning the evacuation of materials resulting from abrasion, however, basal melt water may be more efficient than glacier flow and could be decisive for overall erosion rates. The latter is almost certainly true for local glacial erosion to large depths, which requires linearly concentrated effects as induced by pressurized water flowing (even upslope) in subglacial channels or sheets under the influence of hydraulic gradients in glaciers. The erosion of glacial troughs with beds far below sea level is a fascinating example, quite often revealing V-shaped fluvial cross sections in glacially polished rock (Figure 18).

Fig. 18: Fjords in Tracy Arm (Southern Alaska) showing V-profiles.

Extreme linear bedrock incision with gorges more than 100 m deep but only a few meters wide are known from places in the Alps (Figures 19, 20) and can only be explained by concentrated effects of pressurized subglacial melt water. Such effects of subglacial melt water are poorly treated in the scientific literature about glacial erosion and need much more attention in the future. As hydraulic gradients governing subglacial water flow tend to be higher near steeper glacier margins and as discharge generally increases towards ice margins, subglacial meltwater erosion is expected to be strongest in near-frontal glacier parts with temperate beds and especially during more humid advance periods in the Alps with warmer and wetter glaciers, i.e. within the region of Alpine to pre-Alpine lakes rather than at ice margins of the cold-dry terminal phase.

Fig. 19: Narrow gorge at Lower Grindelwald Glacier.

With the polythermal piedmont glaciers characteristic for the cold-dry conditions at LGM selective linear glacial erosion is likely to occur (Sugden & John 1976). This implies that temperate basal ice and subglacial melt water with erosive capacity are more likely to develop in pre-existing valleys with thicker ice than on ridges and uplands in between with thinner ice cover. The main question relates to the likelihood of new valleys forming pro- or subglacially. Furthermore, the formation of subglacial permafrost underneath cold/thin ice margins not only induces a sharp ice flow discontinuity between sliding/non-sliding parts of the glacier base but also a barrier for water and sediment flux underneath ice margins (Haeberli 1981; Boulton & Caban 1995). Such questions can only be treated using high-resolution 3D, thermo-mechanically and ice-bed coupled transient ice flow models as combined with fluvial erosion models for complex topography. Ice-bed coupling should especially also include interactions of ice with groundwater, melt water erosion, sediment flux and latent heat due to deep ground freezing/ thawing. Qualitatively reasonable is the assumption that glacier extents beyond LGM could lead to warm subglacial conditions with comparably strong erosion at sites with non-erosive cold-based ice under LGM conditions.

Fig. 20: Narrow gorge "Aareschlucht" from Ice Age Aare Glacier.

5 Conclusions and some key questions concerning modelling of glacial erosion in connection with sites for radioactive waste disposal in northern Switzerland

The principal boundary conditions concerning model simulations of glacial erosion under conditions of the Most Extensive Glaciation (MEG) and ice extent during the Last Glacial Maximum (LGM) in northern Switzerland are

- a very dry-cold climate under the influence of a frozen-over Atlantic Ocean;
- large, flat, polythermal to cold piedmont glaciers with small mass balance gradients / mass turnover and slow flow rates;
- periglacial permafrost down to depths of up to 150 meters; and
- correspondingly altered groundwater and geothermal conditions.

Among the key challenges for treating effects of deep erosion at specific sites using numerical model calculations are the following questions:

1. Observations and measurements:
   - what are the main processes of sediment flux (input-transfer-output) in an entire glacier system?
   - what are the relative importance of erosion and sedimentation by glaciers: where are rock and sediment beds likely to develop?
   - what are the glacial and periglacial contributions to overall catchment-area denudation?
   - what are the relative contributions of spatially extended abrasion and linearly concentrated erosion by pressurized subglacial melt water to overall glacial denudation and locally extreme depth erosion?
   - what are characteristic glacial erosion rates in soft sediments, coarse morainic deposits or glacio-fluvial gravels, fractured or soft bedrock, massive or hard bedrock?
2. Modelling
   - what steps are necessary to optimally couple transient, 3D ice flow models with respect to thermo-mechanical aspects (sliding/non-sliding) and ice/bed-interactions (permafrost, groundwater, geothermal heat including latent heat effects)
   - what are the effects of subglacial and ice-marginal permafrost on basal flow continuity, water and sediment flux?
   - how can erosion by pressurized subglacial melt water flow be incorporated in models of glacial erosion?
   - what is the likelihood of new valleys forming under conditions of selective linear erosion of polythermal glaciers?

The planned Nagra/UZH Workshop on Glacial Erosion Modelling is expected to assess the possibilities of reaching realistic near-future progress about such research questions and to recommend corresponding steps to be undertaken.

6 References

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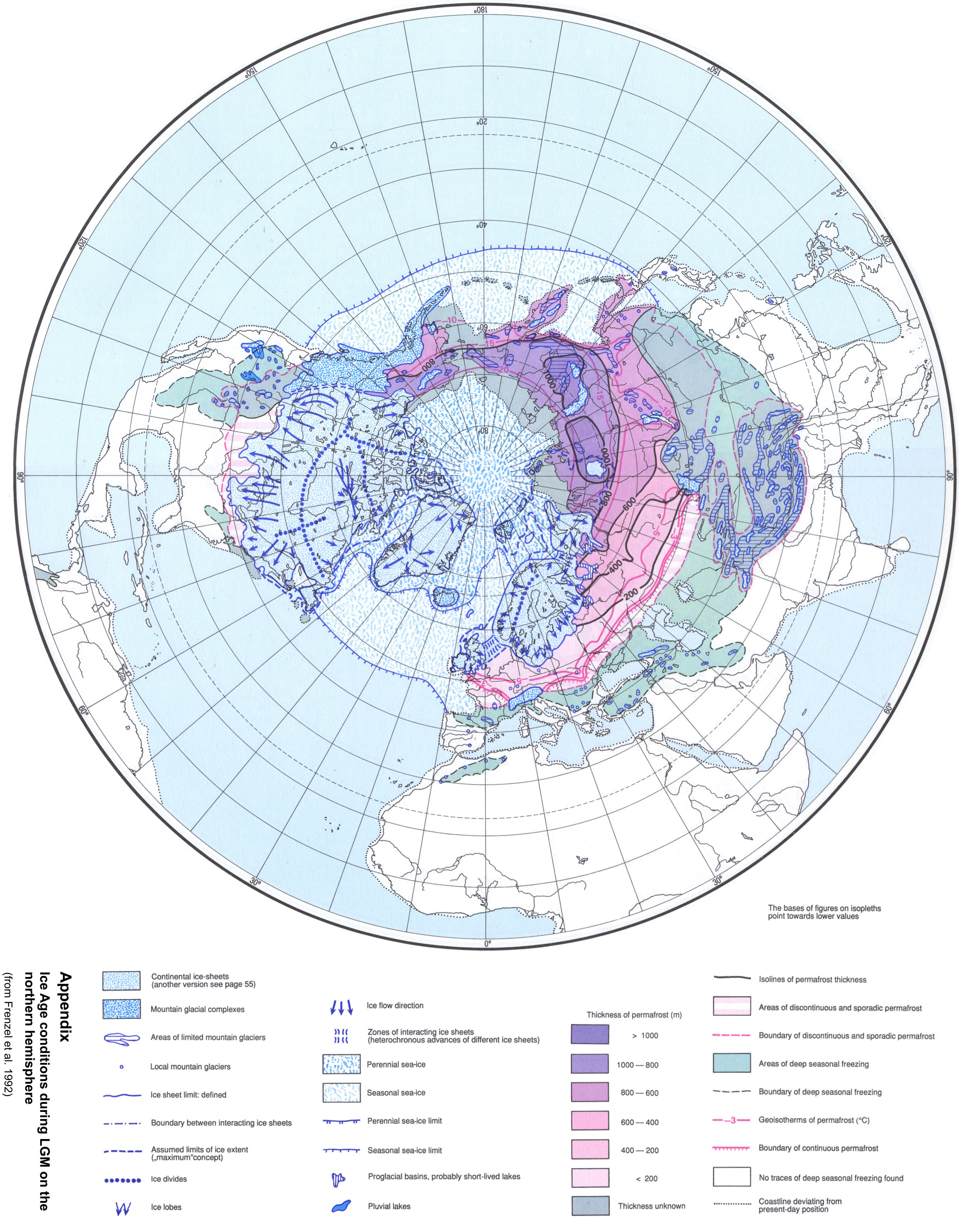
MAXIMUM COOLING OF THE LAST GLACIATION

(about 20,000 to 18,000 yr B.P.)

GLACIATION AND PERMAFROST

GLACIATION by O. Conchon, R. Fulton, M.A. Faustova L.L. Isayeva, J.E. Mojski, S.C. Porter, I.I. Spasskaya, S.N. Timireva, A.A. Velichko, W. Zagwijn
PERMAFROST by V.V. Baulin, N.S. Danilova, V.P. Nechayev, T.L. Péwé, A.A. Velichko



Appendix

Ice Age conditions during LGM on the northern hemisphere

(from Frenzel et al. 1992)